# Application of the Biosonar Measurement Tool (BMT) and Instrumented Mine Simulators (IMS) to Exploration of Dolphin Echolocation During Free-Swimming, Bottom-Object Searches

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**Expanded Abstract:**

Bio-inspired signal processing is based on an understanding of an organism's strategy for task completion using a particular sensory modality and the physiological mechanisms underlying the processing of sensory-acquired information. Dolphins possess a biological sonar system that is highly effective at submerged object detection and identification, is operational in open water to very shallow water (VSW) zones, and is capable of finding buried targets. Due to the ability of the dolphin to out-perform man-made systems at submerged object detection and identification, the United States Navy has placed considerable effort into understanding dolphin biosonar (echolocation).

Research work conducted by the Navy has addressed the characteristics of echolocation clicks, mechanisms of click production and echo reception, and the adaptive production of clicks relative to the echoic task performed. The majorities of the research efforts are traditionally confined to enclosed pen environments and often require limitation of dolphin movements via hoop, or biteplate, stationing devices to control geometries. This imposes an artificiality that removes dolphin motion from search strategy analysis. As such, very little quantitative data is available for when dolphins conduct free-swimming, open water acoustic searches.

These factors reduce the richness of potential information that can be obtained from characterizing echolocation of a free-swimming animal in a natural environment. Under such conditions, information obtained on animal movement, click production, echo reception, and reception of clicks at an insonified target can provide detailed information on dolphin echolocation that can be data mined for biosonar search strategies under real-world conditions. Results can be applied to the development of signal processing algorithms and adaptive search strategies that improve the mine hunting capability of man-made naval assets.

The Biosonar Measurement Tool (BMT) and Instrumented Mine Simulator (IMS) are two instrumentation packages used in dolphin echolocation experiments. The BMT allows the movement and echolocation strategy of a target-hunting dolphin to be recorded without hampering motion through the search field. The IMS records echolocation clicks at a targeted mine simulator.

The experimental design employed on BMT trials involves open-water trained dolphins, dolphin trainers, and a surface workboat. The surface workboat is utilized to transport, or boat follow, an animal to a work area and is the platform from which the work area is pre-configured. The workboat is instrumented with a Differential Global Positioning System (DGPS), digital compass, pitch and roll sensors, and a waterproof computer. Pre-configuring for a session of multiple trials involves the placement of several surface floats (swim floats) and bottom mine simulator targets at measured DGPS locations. Mine simulator targets include a "standard" target, which is a PDM-2 mine simulator. This target was selected as the standard because of its ease of handling and its relatively aspect independent acoustic character (due to the major echo being from the metallic sphere portion of the mine simulator). Other mine simulator targets were employed on a probe trial basis. These included aspect dependant simulators, and IMS instrumented Manta and Rockan mine simulators.

The experimental design used to investigate dolphin echolocation strategies during target detection and identification is dubbed "hide and seek" [1]. One, of two, dolphin subjects is taken out to a pre-configured location within San Diego Bay. A trial consists of positioning the workboat 20 to 60 meters away from one of the surface swim floats. A swim float marks either a positive station (i.e. it has a mine simulator within 3 to 30 meters from the swim float) or a negative station (a mine simulator is not located nearby). For non-IMS probe trials, the probe target was similarly associated with a swim float. IMS probes were always placed ~30m from the swim float. The dolphin is trained to station on the port side of the workboat and take the BMT into it's mouth at the start of a trial. The BMT signals the trainer via a LED flash sequence that the trials data collection has started. The trainer sends the animal on the trial while an assistant simultaneously toggles a switch on the workboat computer indicating the dolphin has begun the trial. This start point is also logged with a DGPS location.

The dolphin is trained to swim towards the surface float while conducting an acoustic search for bottom targets. The dolphin reports a positive "target present" by whistling during the trial. Another assistant trainer listens for the response with a hydrophone and headset. A bridge signal is provided to the dolphin if the positive response is correct. The dolphin returns to the work boat immediately after issuing the positive whistle response. The positive whistle response is also recorded by the acoustic sensors of the BMT and imbedded into the acoustic data stream. This acoustic mark aides in post trial analysis by indicating the point in time that the dolphin made the positive response.

If the dolphin does not find a target (i.e. does not report a positive "target present"), it is required to swim to, and around the surface float before returning to the workboat. Typical trials range in time from several seconds to 90 seconds in duration.

When the dolphin returns to the workboat, another DGPS synchronization is taken. The BMT is taken from the dolphin and the on-board data is uploaded into the workboat computer. The DGPS data marked at the start and end of a trial are employed to reference the BMT collected underwater position data into the earth (GPS) coordinate system.

Fig. 1 provides an image of the various components of a trial. Fig. 1 is a snapshot of a 3 dimensional interactive replay capability of the dolphin trial created post session in the laboratory. The 3 dimensional replay capability is further described in the data analysis section of this abstract.

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The BMT is conceptually a more sophisticated development based upon the earlier Attitude Range Monitor (ARM) effort [2] The BMT employs similar methods for attaching instrumentation to the dolphin, namely via mounting underneath a bite plate that the dolphin carries in its mouth. Fig. 2 is a photograph of the BMT showing the configuration of the bite plate to the rest of the instrument.  This design was favored over alternatives (such as back pack mounting) for simplicity, safety and comfort of the dolphin.  The dolphin is free at any time to open its mouth and "drop" the instrumentation package.

The Biosonar Measurement Tool (BMT) was developed to record a wide variety of sensor data from a free swimming dolphin engaged in a bottom target detection task.  Sensor data include 3-dimensional attitudes and motions of the dolphin (heading, pitch, roll, depth and velocity) and three channels of passive sonar data (the outgoing echolocation clicks on one channel, and a biologically inspired high gain binaural receiver on two channels for collecting echoes).   A low-risk approach to the development of the BMT electronics was employed primarily using Commercial Off The Shelf (COTS) electronics.  The primary attitude sensor is a Crossbow ® 9-DOF navigation sensor (Attitude Heading Reference Unit).
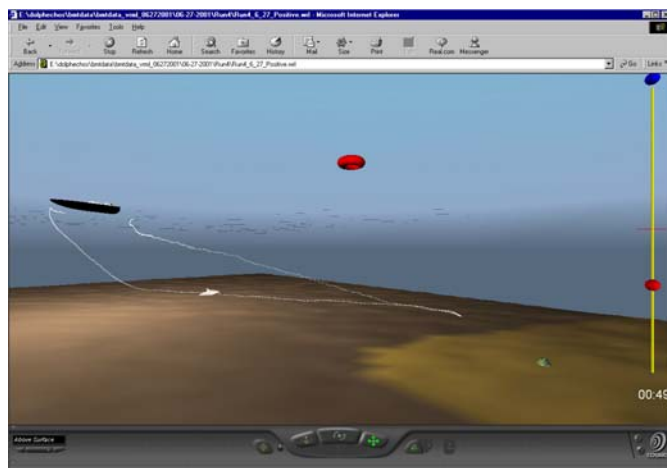


Fig. 1 - Image of dolphin echolocation trial showing the various components of the system (dolphin, dolphin path in white, surface work boat, surface swim float and bottom target).



Fig. 2 – BMT device showing bite plate mount method, outgoing click monitor (on projected stalk) and binaural high gain sonar receivers.

This unit provides computed Euler angles of heading, pitch and roll, as well as raw outputs of a temperature sensor, and three axes each of magnetic data, acceleration data, and angular rate data.  Two additional underwater sensors are used to directly

measure depth (a 0-50 pounds per square inch gage pressure sensor with a resolution of ~3") and velocity (a fiber optic based propeller rotation device).  Acceleration data allows potential for improving the navigational accuracy because the dolphin velocity vector can potentially vary from the velocity vector measured in line with the mouth by the velocity sensor.  Furthermore,  as has been done with whale tag data (ref. 3), biologic analysis of swim motion can be applied to motion events that are evident in the data stream (e.g tail thrusts).

The three channel passive acoustic monitoring system allows for the continuous, simultaneous measurement of each channel to 16-bits of resolution at a sample rate of approximately 314 KHz.  Sigma delta analog to digital over sampling converters are utilized providing a bandwidth of approximately 150KHz for each channel.  All channels are bandpass filtered at 12KHz on the low end (to reduce the effects of boat motors, etc. in the bay) and 150KHz on the high end for anti-aliasing purposes.

Outgoing echolocation clicks are recorded on a small, low gain, omni-directional hydrophone (Reson TC4013)  placed 1 m in front of the animal on the animals maximum response axis for outgoing signals [4].   This allows outgoing echolocation clicks to be recorded unsaturated (saturation occurs at 210dB re 1uPa source level) while maintaining high fidelity for detailed post analysis of each outgoing click.

The two high-gain, directional hydrophones, which are modeled after the dolphin auditory system, are mounted on the front of the BMT package for receiving dolphin-generated echoes and ambient sound data.   The directional hydrophones have beam widths comparable to behaviorally measured dolphin receive beam patterns [5].  The spacing between biomimetic receivers, 12.5cm, approximates the spacing of the dolphins inner ears.   The gain setting of the biomimetic receiver is such that digitized data saturates at approximately 155dB re 1uPa. Due to the wide dynamic range realized using 16-bit converters, and the relatively short range of the sonar system (under 100meters), time varying gain was not utilized.  The higher gain, and directivity index associated with the directional receiver allows for detecting small target strength targets (such as the mine simulators employed) out to ranges in excess of 60 meters.

COTS electronics are also utilized for the control computer, which is a  conduction cooled 6U VME board with a Motorola PowerPC processor.  The VxWorks Real Time Operating System (RTOS) was used for software development. Another COTS 6U VME analog to digital converter board is utilized for acquiring the three acoustic channels of data. Custom electronics were required only for pre-amplification and signal conditioning of the acoustic channels, and the depth and speed sensors.  A battery pack utilizing 10 D size cells powers the unit via a COTS PC104 DC-DC converter (which has a switching frequency above the highest sonar frequency of interest).  Total power consumption is approximately 35 watts and the device can run for more than an hour on one battery charge.   In excess of 20 trials are possible on a single battery charge.  The batteries are housed in a set of sealed compartments separate from the electronics.  This provides both a margin of safety and facilitates changing of the batteries in the field if needed.  A wet mate-able underwater connector is utilized to connect to the boat computer and upload the data collected after each trial over standard 100Base-T Ethernet connectivity. Time to upload the maximum amount of data collected (242MB) is approximately 25 seconds, which is acceptable in terms of animal training concerns and the delay necessary between successive trials.

The Instrumented Mine Simulators (IMS) used in bottom-object search scenarios were developed approximately 18 months after initial development of the BMT.  These instrument packages make use of a single omni-directional receive data hydrophone (Reson TC4013A-same as used for outgoing click monitoring in the BMT) to sense the acoustic signals.  The gain on the hydrophone pre-amplifier is set higher than that on the BMT so the dolphins incoming echolocation signals can be recorded when the dolphin is tens of meters away.  The same sigma delta

analog-to-digital converter chips used in the BMT are utilized. However, as this package does not undergo high dynamics, it has a relatively simple COTS heading, pitch roll sensor and no depth, or velocity, sensors. To make the IMS electronics package smaller and less expensive than the BMT, a COTS PC104+ Pentium based control computer and data acquisition boards were utilized. A SHARC-based PC104+ DSP card was utilized for acquiring the single 312.5 KHz sample rate sonar receiver. While the DSP is overkill for the in-field data collection task, it allows for future designs of a newer BMT (BMT mod.1) as well as potential for future real time signal processing within biomimetic sonar systems.

The same PC104 DC-DC converter utilized in the BMT is utilized in the IMS. However, the IMS includes a separate acoustically commanded wake/sleep subsystem. This allows the IMS to be placed out in the field for weeks at a time and acoustically waking it up before conducting dolphin sessions. The IMS automatically shuts off 18 minutes after being woken up. The IMS packages contain a small 20 Gbyte hard drive for data storage.

## DATA COLLECTIONS

Data has been collected with two dolphins engaged in free-swimming, bottom-object searches in conjunction with the deployment of both the BMT and IMS systems. Preliminary results demonstrate distinctive search strategies between the two animals. One strategy is characterized as a rapid search ( < 10 s) with low click production and variable distribution of energy across the frequency range of echolocation (~20 – 120 kHz). The other strategy is comparatively slower, on the order of tens of seconds, and is characterized by the copious production of stereotypical clicks with dominant energy between 30 – 60 kHz. The latter strategy also demonstrates a lower false alarm rate. Prior training histories are suspected as contributing to differences in search strategy, but compromise to the auditory system cannot yet be discounted in the latter animal. In conjunction with BMT data, data from the IMS targets are currently being evaluated to assess adaptive variation in click production as targets are acoustically encountered, determine the characteristics of signals returned by insonified targets, and assess the minimum information required by an echolocating dolphin to detect and identify a target of interest. The ultimate goal of this research is to design new signal processing algorithms and augment current algorithms through incorporation of dolphin search strategies and click-echo dynamics.

## DATA ANALYSIS

Data collections recorded by the BMT are uploaded upon return from the field. Due to the complexity of the data (full three dimensional positional data as a function of time, acoustic outgoing and acoustic binaural receive data) a two stage analytical process is utilized. In the first stage a "Virtual replay" of the trial is generated to provide researchers with good situational understanding of the trial and help point to specific areas of the trials for more detailed analysis. The virtual replay utilizes C code to translate the BMT sensor data into Virtual Reality Modeling Language (VRML) code. Any web browser, properly configured with a VRML plug-in, allows interactive 3-D replay of the trial. The virtual replay is run at a speed 7 times slower than real time to allow listening to the binaural high gain receive data. Experienced researchers have aurally detected targets of interest when they are insonified. The visual data consists of a lifelike 3-D model of the dolphin (rigid for simplicity), a surface work boat, the mine simulator on the seafloor, and the swim buoy. The VRML model is totally interactive allowing the viewer to choose the camera viewpoint, back up, or fast forward the replay, etc. Fig. 1 provides a screen capture of a virtual replay in the browser window showing the dolphin, the dolphins path in white (able to turn path display on/off), the work boat, the swim float and a mine simulator on the bottom.

The second phase of the analysis is detailed, quantitative analysis of the various sensors. Fig. 3 is a Matlab 3-dimensional plot which provides underwater positional data derived from the AHRS depth and velocity sensors. Fig. 3 data is referenced to X,Y and Z coordinates of 0,0,0 at the start of the trial. Data not readily apparent in Fig. 3 are the dolphins velocity, heading and pitch/roll attitude. Matlab plots are available for all of the dolphin underwater swim positions and attitudes.

Fig. 4 provides an overview of the three acoustic channels of data for the trial presented in Fig. 3 (45 second trial). Due to the high sample rate of the acoustics, the three channels of acoustic data require approximately 80Mbytes of storage.
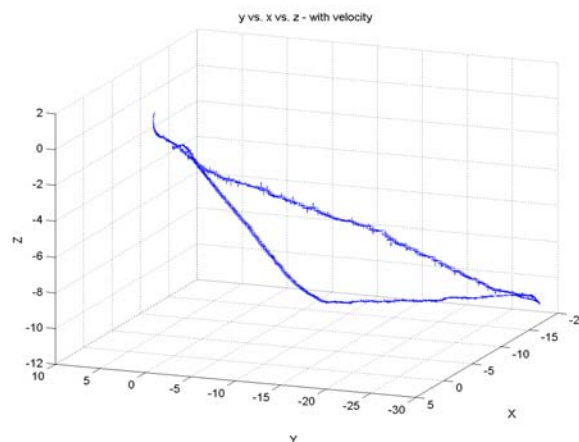


Fig. 3 – Sample 3-D Matlab plot of sample trial. Includes true heading, pitch, roll, depth and velocity information at 80Hz rate (velocity and depth at 20Hz rate).
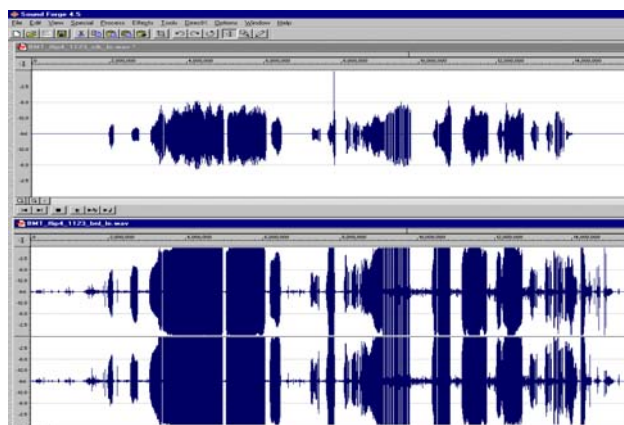


Fig. 4 – Acoustic data for the 45-second trial depicted in Fig. 3. Outgoing click monitor shown at top. Binaural high gain, directional receivers shown on bottom.

Fig. 5 provides plots of the source level and inter-click intervals for all outgoing clicks from a representative short trial. The trial was a positive trial, and the red arrow in Fig. 5 shows where the dolphin's positive whistle response was made during the trial. Source levels are over 205dB re 1uPa and the inter-click-intervals are around 40 milliseconds at the time of the whistle. Fig. 6 provides spectral data for clicks extracted from the click train illustrated in Fig. 5. The lower amplitude start up nature of the click production mechanism is readily apparent.
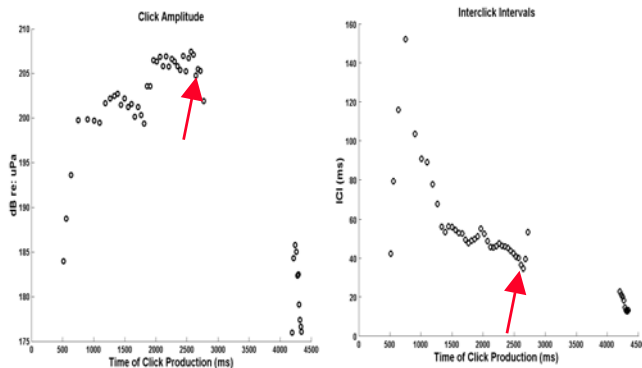
Fig. 5 – Sample outgoing click source level and inter-click intervals.

The data also show a large variation in the spectral characteristics of the outgoing clicks, starting with high frequency content, shifting to very broadband signals, then predominantly low frequency content [6]. The strongest high frequency unimodal outgoing clicks then appear a bit before the dolphins whistle response. Analysis continues to determine if a correlation between the frequency dependent energy distributions and the animals searching mode exists (search, acquire, confirm).
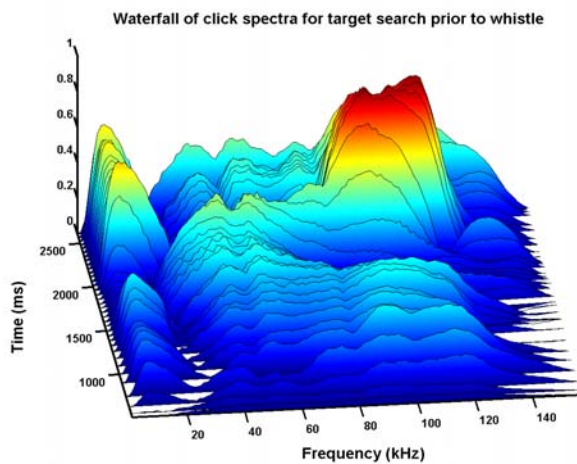

Fig. 6– Sample spectra for a sequence of outgoing clicks illustrating variability possible in the spectral domain.

The two channel, dolphin biomimetic binaural receiver model, also allows beamforming, or bearing estimates, to determine the relative angle to echoes due to the inter-aural time difference in arrivals. Straight forward cross correlation techniques have been employed, as have more elaborate adaptive techniques based upon a Chirp Corporation algorithm.

Data recorded by Instrumented Mine Simulators is also uploaded in the laboratory after recovery. Signal processing tools are run on the data to synchronize the mine data with the BMT data. This is accomplished by roughly aligning the time of day based upon internal clocks and then correlating inter-click intervals recorded at the IMS with inter-click intervals extracted from the BMT acoustic data stream. Fig. 7 provides a sample of acoustic information arriving at an instrumented mine simulator that has been synchronized with the BMT data. The top part of Fig. 7 shows the BMT outgoing click train along with the heading, pitch and roll information. The pitch and roll data are centered around 0 degrees, while the heading data varies from approximately 140 degrees down to 40 degrees while the dolphin is searching. The lower part of Fig. 7 shows the IMS incoming acoustic data with the same BMT heading, pitch and roll data. The IMS is at a true bearing angle of approximately 50 degrees from the location of the BMT at the time of this data. One sees the dolphins acoustic search pattern in terms of head motion

scanning from 100 degrees heading down to 50 degrees. The IMS received signals are maximized when the BMT is pointing at 50 degrees heading. The dolphin then scans back up towards 100 degrees and comes back to 50 degrees. Again, the IMS data shows maximal incoming signal as the dolphin scans back onto the IMS target heading. It is interesting to note that the trial ends at this point in terms of the animal's acoustic search; the dolphin ceased echolocation, turned around and headed back to the work boat.

*SUMMARY*

Data have been collected from two dolphins engaged in free-swimming, bottom-object searches in conjunction with the deployment of both the BMT and IMS systems. Preliminary results demonstrate distinctive search strategies between the animals. One strategy is characterized as a rapid search ( < 10 s) with low click production and variable distribution of energy across the frequency range of echolocation (~20kHz – 120 kHz). The other strategy is comparatively slower, on the order of tens of seconds, and is characterized by the copious production of stereotypical clicks with dominant energy between 30 – 60 kHz. The latter strategy also demonstrates a lower false alarm rate. Prior training histories are suspected as contributing to differences in search strategy, but compromise to the auditory system cannot as of yet be discounted.
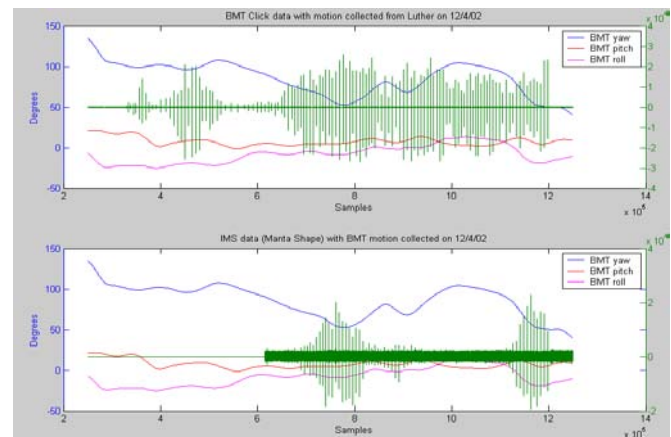

Fig. 7 – BMT outgoing click synchronization with IMS incoming clicks with respect to BMT heading, pitch and roll data.

The instrumentation described herein has been designed to provide quantitative data for free-swimming dolphins conducting mine-hunting tasks. The data allow researchers never before seen insight into what the dolphin actually does when free swimming and hunting for mine-shaped targets. The richness of the data is unparalleled and requires continued in-depth analysis. The data allows researchers to better understand how the dolphin effectively accomplishes object detection and identification tasks. In addition, when researchers have hypotheses on ways to improve mine hunting sonar's, developed algorithms can be applied to the BMT and IMS data to demonstrate how the algorithm performs relative to the dolphin.

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